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Sheila G. Bailey, Francis P. Chiaramonte
and Kenneth J. Davidian
Lewis Research Center
Cleveland, Ohio

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THE INTERNATIONAL SPACE UNIVERSITY'S VARIABLE GRAVITY RESEARCH FACILITY DESIGN

*Sheila G. Bailey**, *Francis P. Chiaramonte†*, and *Kenneth J. Davidian‡*
National Aeronautics and Space Administration
Lewis Research Center

ABSTRACT

A manned mission to Mars will require long travel times between Earth and Mars. However, exposure to long-duration zero gravity is known to be harmful to the human body. Some of the harmful effects are loss of heart and lung capacity, inability to stand upright, muscular weakness and loss of bone calcium. A variable gravity research facility (VGRF) that would be placed in low Earth orbit (LEO) was designed by students of the International Space University 1989 Summer Session held in Strasbourg, France, to provide a testbed for conducting experiments in the life and physical sciences in preparation for a mission to Mars. This design exercise was unique because it addressed all aspects concerning a large space project. This report describes the VGRF design which was developed by international participants specializing in the following areas: the politics of international cooperation, engineering, architecture, in-space physiological, material, and life science experimentation, data communications, and business and management.

*Physicist, Photovoltaic Branch, Power Technology Division, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio, 44135-3191.

†Aerospace Engineer, Microgravity Fluids Branch, Space Experiments Division, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio, 44135-3191, AIAA member #300133253.

‡Aerospace Engineer, Launch Vehicle Research Branch, Space Propulsion Technology Division, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio, 44135-3191.

NOMENCLATURE

0-g	zero gravity	N	Newtons
1-g	one Earth gravity	r	radius of rotation
a	centripetal acceleration	ω	rotation rate
g-level	gravity level	Subscripts	
I	Moment of Inertia	x	x axis
mt	Metric Tons	z	z axis

INTRODUCTION

The 1989 International Space University (ISU) convened July 1, 1989 in Strasbourg, France at the Université Louis Pasteur. One hundred twenty five students from twenty-five countries came to interact, study, and participate in a multinational, multidisciplinary educational experience in all aspects of space. An international faculty presented core lectures in eight space disciplines: Architecture, Business and Management, Engineering, Life Science, Policy and Law, Resources and Manufacturing, Satellite Applications, and Physical Science. These provided a common base of knowledge for all the students. Advanced and plenary lectures given by world renowned experts in each of the eight disciplines, provided specialized study in each student's particular area of interest.

To promote interdisciplinary integration and interaction between students, two design projects were chosen whose goals were to utilize their talents and creativity. The scope of each design project included mission objectives, engineering designs, management organization structure, project finances, program implementation, and system operations. The selected design projects for the 1989 ISU were a lunar polar orbiter and VGRF. The name for the VGRF selected by its participants was Newton. Members of the international faculty served as expert advisors and additional support was provided by Departmental Assistants, who were 1988 ISU alumni. A list of the

students, Departmental Assistants, and ISU faculty involved with the Newton VGRF design project is provided in Table 1.¹

The international nature of this project, encompassing all eight space related disciplines listed above, led to a system design unrestricted by any one national space program. Recent VGRF design studies from the United States (US) assume that all of the components will be launched on the US Space Shuttle.^{2,3,4} This restricts component size and system design, and potentially increases the number of launches needed for assembly since expendable launch vehicles (ELV) were not considered. The focus of this paper is to summarize the results of the Newton-VGRF design project. Although the overall design and feasibility of the VGRF will no doubt receive its share of support and criticism, the entire project was a success on the basis of the intangible value of the achieved cooperation, collaboration, and gained understanding among the diverse student and faculty participants.

MISSION OBJECTIVES

Exposure to long duration 0-g is known to be harmful to the human body. Some of the major problems are loss of heart and lung capacity, inability to stand upright, muscular atrophy, and loss of bone calcium.^{5,6} This could result in the inability of space travelers to function effectively after a long-duration mission and still return safely to Earth.⁷ On orbit conditioning requirements to maintain physical fitness can potentially dominate the majority of an astronaut's waking hours. Earth-bound medical treatment partially alleviates some of the problems but the countermeasures are not totally effective and free of side-effects. In view of the renewed enthusiasm for a manned lunar base and human spaceflight to Mars, it is imperative that the debilitating effects of long duration reduced gravity exposure be minimized or counteracted.

Creation of artificial gravity in a rotating centrifuge or spacecraft is one possible way to coun-

teract the harmful effects of 0-g on the human body.⁸ The g-level, spin rate and duration compatible with human performance and efficient engineering design, must be determined before a long duration mission to the Moon or Mars can be undertaken. Newton was designed to permit experiments on human beings and animals at different g-levels and spin rates.

The VGRF will be deployed in LEO to provide an easy access testing ground for studies of human adaptation to artificial gravity during long-duration space-flight, e.g. a mission to Mars. Newton provides the capability to vary both the radius and rotation rate of the facility with the constraint of providing 1-g at a maximum rotation rate of 3 rpm. Newton's design encompasses both lunar and Martian g-levels sequentially. Newton would provide unique variable gravity conditions not available in other space-based facilities. It accommodates six international crew members. Political and financial constraints dictated a simple, minimal structure.⁹

In addition to finding a practical solution to long duration human exposure in 0-g, the VGRF would be used to support physical and material science research at a number of gravity levels. Manufacturing and fundamental science experiments would be conducted on the VGRF to develop gravity dependent technologies to support a human settlement on the moon or Mars. Examples of such technologies include atmospheric gas processing and soil utilization. Easy experimental hardware exchange has been designed into the facility to allow for a flexible progression of experimental goals.

The anticipated Mars mission development time-line drove the end-point decision for Newton's operational lifetime as illustrated in the project schedule shown in Fig. 1.¹ Thirteen years, starting in 1990, were allotted for the development of international agreements and the completion of all design phases (phase A beginning in 1992, phase B in 1994, and phases C/D in 1998). Assembly and checkout of the facility would take place between the years 2003 and 2004.

Newton would be operational for nine years (until 2013) at which time, seven years would be allotted to build the Mars vehicle. This schedule provides for the commencement of the Mars mission in the year 2020.

INTERNATIONAL ORGANIZATION AND STRUCTURE

Political Structure

The political structure of the VGRF was based on goals, objectives, and requirements expressed in statements of intent by countries with active space programs. Primary partners, those who would have a need for the facility, include the only two nations with stated goals of sending human beings to the planet Mars: the US and the Union of Soviet Socialist Republics (USSR). Secondary partners are other nations which are actively involved in developing their own space program, have their own astronaut program, and have expressed an interest in a manned mission to Mars: the European Space Agency (ESA), Japan, and Canada. Nations with space programs which have not been included in the top two echelons of the VGRF political structure, due to the lack of an astronaut program and the lack of a statement expressing an interest in a manned Mars mission include China and India. These countries, as well as corporations, universities, or other agencies, can participate in the VGRF project after negotiation with the primary and secondary partners of the project.

To produce a legally binding document without having to endure the problematic acceptance procedures of a treaty, a bilateral Statement of Intent (SI), as defined in the Vienna Convention of 1969,¹⁰ was selected as the document which pairs the US with the USSR as initiating partners and envelopes the goals, purposes, and principles of the VGRF mission. The agreement, to be signed in 1991, would recognize the need for international cooperation, the peaceful (non-military) operation and use of the facility, and the value of the biomedical data that on board experiments may

yield. Both countries would agree in the SI that cooperation on the VGRF project would provide a test-bed for future cooperative ventures. The US and the USSR would then extend an invitation to Canada, Japan, and ESA to join the VGRF program as partners.

In order to detail the rights and obligations of the five partner nations, as well as to define the specifics relating to the cooperative agreement amongst the nations, a multilateral intergovernmental agreement would be drafted. This document would be signed in 1994 and reference the SI between the US and the USSR, the acceptance by the governments of Canada, Japan, and ESA, the Outer Space Treaty,¹¹ the Astronaut Rescue Agreement,¹² the Liability Convention,¹³ and the Registration Convention.¹⁴

Most of the total expenditure would be required for phase C/D; the production, assembly and integration of Newton. Signing of the memoranda of understanding in 1996 by each country would allow initiation of this process.

Organizational and Management Structure

The management structure would be comprised of various levels of decision making bodies whose purposes range from purely technical (for example, integration of subassemblies) to purely political, as shown in Fig. 2.¹ The Directorate consists of one member from the US and one from the USSR and intervenes only when the governing board cannot reach a consensus. The governing board, consisting of one member from each of the primary and secondary partners, was created to make final decisions on program areas affecting two or more partners.

In order to manage Newton's development and operation, the specific duties of each participating country would be assigned via work packages. The content of each nation's work package, detailed in Table 2,¹ has been designed to utilize each country's demonstrated technical strengths. All facility and ground operation costs would be distributed proportionately among the partners of

the Newton project.

To maintain participative equality, headquarters will be located in Vienna, Austria during development and operation phases of the VGRF project. Although both ESA and the US possess communications networks which could meet the VGRF's needs with no development or construction, the European network was selected for political reasons of just return. An existing facility in Toulouse, France was chosen as the site for the control center. Individual training sites will be used for the initial crew training, but training of the entire group together will take place at a training facility in an undetermined location.

Four official languages for the ground-based operations of Newton's development and operation phases were chosen, based on prior international scientific cooperative missions: English, French, Japanese, and Russian.

Legal Issues

Each of the nations participating in the VGRF project, except the USSR, have technology transfer regulations. By far the most stringent is the Arms Export Control Act of the US.¹⁵ Even though the design and construction of Newton is meant to isolate each system from the other, there are inevitable amounts of interreliability. Data management, life support, and power systems are a few examples of systems which cannot exist independently of the others. To minimize technology transfer, the US would launch its own hardware along with that of the Japanese and some Canadian hardware. The USSR would launch all USSR, ESA, and the remaining Canadian hardware. To provide an incentive for international cooperation, to reduce overall costs, and to improve Newton's safety and reliability, space on board the VGRF or financial compensation could be traded for shared technology which is deemed not highly sensitive by the country who owns it.

Environmental protection and liability issues would be addressed through adherence to inter-

national space treaties. For example, all organic and inorganic refuse produced on board would be returned to Earth as outlined in Article IX of the Outer Space Treaty.¹¹ The Liability Convention of 1972,¹³ to which all the participating nations in the VGRF project are signatories, states that "Each State Party to the [Outer Space] Treaty that launches or procures the launching of an object into outer space...is internationally liable for damage to another State Party to the Treaty or to its natural or juridical persons...". Therefore, it is applicable to the Newton facility. Each member state will register its own portion of the VGRF, thereby maintaining jurisdiction and control of their portion and personnel.

SCIENCE REQUIREMENTS

The purpose of constructing and utilizing the VGRF, illustrated in Fig. 3,¹ is to achieve the following goals:

- primarily, to determine a solution to the deconditioning effects of long term 0-g on the human body using artificial gravity, for the future purpose of a manned Mars mission and
- secondly, to support long duration manned missions by conducting research in life and physical science processes and space manufacturing at a number of g-levels including lunar and martian gravities.

To meet these goals, the following major operational requirements were imposed on the system design:

1. a range of constant artificial gravity environments including lunar, martian, and earth gravities,
2. a range of rotation rates at each g-level with a minimum of 3 rpm to attain 1-g,
3. the duration of a gravity environment from a few months to several years,

4. six crew members on board, and
5. experiments to be accommodated include human, animal, plant, and physical science manufacturing.

The data gathered would be used to plan a manned mission to Mars and assist in the design of the spacecraft(s).

Life Science

The Life Science experiments to be conducted on Newton are divided into two major categories: a Mars mission enabling studies and a life science research program. The Mars mission enabling program focuses on human physiology, medical care, psycho-social studies and advanced life support. The life science research program will emphasize basic science studies with animals, plants and cellular systems. Experiments would be conducted over a range of low gravity environments.

The Mars enabling studies must determine how to keep people healthy for a three year manned mission to Mars. From previous space flights, it is known that physiological adaptations occur which result in muscle atrophy, bone demineralization, cardiovascular deconditioning and neurovestibular system changes.^{5,6,7} Data to be recorded is the rate of deconditioning of all the bodily systems with respect to time as a function of g-level, rotation rate and radius of the facility.

Analyzing the effects of reduced gravity on humans would include studies on the entire body and separate systems which are: cardiovascular, endocrine, gastrointestinal, genito-urinary, hematological, immunological, muscular, neurovestibular, pulmonary and skeletal. Initially, partial gravity will be used as a countermeasure to the anticipated decline in performance of a specific system.^{8,16,17} However, if significant deconditioning occurs, then countermeasures, such as routine exercise, would be implemented. Each system would be studied by conducting tests. For example,

measurements for cardiovascular studies include heart rate and cardiac output. Blood samples are needed for the endocrine, hematological, immunological, genito-urinary, and pulmonary systems. The voluntary muscle and skeletal systems would require non-invasive test methods such as X-ray diagnostics. In the event of illness or injury, a medical care facility is necessary to accommodate the six crew members who would be on board for each six month mission. Medical capability would provide inpatient, outpatient, critical care, and surgical capability for diagnosis and treatment. On board capabilities would include X-ray imaging, microbiology, and hematology labs, operating room facilities and pharmaceuticals. For immediate medical needs beyond the capability of the facility, the crew escape vehicle would transport the patient to Earth.

Because the Mars mission may require three years of space flight in a relatively small spacecraft, psycho-social factors will play a key role. The VGRF would model this scenario. Screening tests would be conducted for astronaut selection including life histories, social compatibility behavior and personality tests. Possible adverse physical effects that could occur include headaches, chest pain, aggression, and sleep disturbances. Preventive measures would include the placement of windows for viewing the outside, reminders of the Earth environment (e.g., music, books), and designated privacy areas for each astronaut. Monitoring the astronauts' psychological well-being would be performed by reports from other crew members, daily logs in each individual's diary, and by use of advanced expert systems for personality evaluation.

The life science research program would perform experiments with animals¹⁸ to gain a better understanding of physiological effects of partial gravity on human beings. Using rats as test specimens, fluid balance and control tests would help explain changes in the cardiovascular and renal systems. Bone demineralization studies would assist in determining the relationship between weight bearing and stress unloading, and growth and remodelling. Data from these experiments

would provide input to the Mars enabling studies program.

Science Processes and Manufacturing

Science processes and manufacturing experiments would be conducted in the variable gravity environment of Newton since human planetary settlements will require resource utilization.

Processes which could be used for a human base on Mars include water extraction from the soil and oxygen processing from the predominantly carbon dioxide atmosphere.¹⁹ For a moon base, resources such as oxygen, water, aluminium-based solid fuel, concrete, iron and glass could be wholly or partially produced from the lunar soil (40% oxygen, 21% silicon and metals such as iron, aluminum and titanium) provided that manufacturing processes are available.²⁰

The goal of the process simulation experiments would provide experience in using the hardware and equipment as well as with the process itself. These experiments would therefore test automation, teleoperations, and remote maintenance procedures as well as demonstrate front-to-back production processes in a partial gravity environment.

Mars and lunar settlements will need plants for foodstuff production, however, the influence of radiation and partial g-levels need to be clearly understood. Furthermore, gravity-dependent basic science such as fluid physics (e.g. boiling), transport phenomena, biotechnology, materials processing (e.g. crystal growth) and combustion, is necessary to support space based processes. Basic science experiments would be conducted to advance the development of critical technologies by improving the fundamental understanding of the phenomena.

FACILITY DESIGN

Newton is comparable with the US led International Space Station Freedom in scale and complexity. Newton's design incorporates political, economic, and schedule limitations as well as functional requirements.

An isometric view of Newton in Fig. 3¹ shows the major hardware components:

- The module section, includes the pressurized habitation, command and laboratory modules where the crew lives and works, the logistics module which holds supplies, airlocks or extra vehicular activity (EVA) module for crew transfer during times of resupply when the facility is despun, a reaction control system (RCS) for spinning and despinning the facility, and two emergency escape vehicles shown in Fig. 4.¹
- The connecting truss provides a rigid but massive rotational arm for the entire facility. Instead of trusses, the use of tethers were explored but abandoned due to stability and control issues.²¹
- The counterweight section, which roughly balances the mass of the module section, is comprised of two empty Energiya core vehicles fitted with mounting hardware to allow attachment to the connecting truss. This section can also be relocated along the truss to attain various gravity conditions within the module section.
- The central despun section was necessary for the location of the photovoltaic panels and the communications transmitting and receiving equipment. Because the center of gravity (CG) will change locations during day-to-day operations as well as during 0-g resupplying operations, this equipment is attached to a moveable pallet which can be precisely controlled and positioned. A major source of CG movement, the burning of five mt of propellant during spin-up, will cause the CG to change location by more than 2 m.

System Budgets

Determination of masses of the different components of Newton were constrained by the rotational stability of the facility. Since the configuration is roughly that of a dumbbell, the rotational

stability of the facility was assured by maintaining a moment of inertia about the z axis, I_z , greater than that about the x axis, I_x . Based on the mass budget, given in Table 3 and mass distribution of Newton, the ratio of I_z to I_x was 1.002. Special attention was given to the alignment of the two Energiya counterweight tanks with respect to the rotational motion of the facility.

Power requirements for Newton were also assessed and specified. Based on a life support system requirement of 25 kW, 50 kW to run the scientific experiments, 78 kW to charge batteries, and 17 kW of various power losses (direct current to alternating current conversion, distance, and power distribution and control assembly), the end of life solar array output was determined to be 170 kW. Addition of a 10% solar array oversizing requirement to account for array degradation over the lifetime of the facility resulted in the total raw power requirement of 187 kW.²²

Orbital Dynamics

Concerns of orbital dynamics are made more complex when the spacecraft being analyzed is very large and itself spinning. Issues of orbit and attitude selection, attitude control, and solar array and antennae pointing are more difficult to resolve when compounded with problems of centrifugal and Coriolis accelerations and facility spin and despin operations. Analysis of the Newton facility included each of these phenomena which affect orbital dynamics.

Governed by the centripetal acceleration equation²

$$a = \omega^2 r \quad (1)$$

maximum spin rate constraints of 3 rpm and g-level requirements of up to 1-g drove the size of Newton to be 200 m in diameter. Centrifugal acceleration of the rotating modules results in the creation of a force pointing outward from Newton's CG. This force is the desirable artificial gravity for which the VGRF is being designed. However, a secondary force is also generated due to the existence of the Coriolis acceleration. This Coriolis force is evident when a person moves along

the radius from the center of rotation, moves tangentially to the rotation, nods their head out of the plane of rotation, or tips their head from side to side.^{17,23} With a linear velocity of 1 m/s and a facility spin rate of 2 to 4 rpm, a Coriolis force of up to 60 N could be felt when walking, sitting, standing, or while tipping or turning the head. This could result in a change of direction of movement (not walking in a straight line or not sitting where intended) or motion sickness.

Due to the lower radiation environment and ease of access from Earth, Newton would be put into orbit at a maximum altitude of approximately 550 km. The scenario of co-orbiting Newton with an existing space station such as the USSR's Space Station Mir was not feasible because the orbital decay of Newton (100 km in six months) was greater than that of Mir (30 km in three months).¹

The ability of both US and USSR launch systems to reach the orbiting facility required its placement to be at an orbital inclination of 51° . This attitude would allow existing and future launch systems to deliver large payloads, including crew, to Newton. The USSR's Energiya can deliver approximately 100 mt to this orbit, the US's Space Shuttle can deliver approximately 15 mt, and the ESA's Ariane 5, when operational, would also be able to deliver approximately 18 mt to this orbit.

Two degrees of freedom are required to point both the solar arrays and the communications antennae. The first degree of freedom must be parallel to the angular momentum of the VGRF at a rotational rate equal to the algebraic sum of the facility spin rate and orbital rate. This despins the solar arrays with respect to the rotation of the truss and aligns their normal component with the projection of the sun direction into the orbit plane. The second degree of freedom, with a pointing capability of 90° , allows direct pointing of the arrays at the sun. To ensure a permanent communications link between Newton and the ground stations regardless of solar array orientation, two

communications antennae located on top of the array mast were required.

Effects which disturb Newton's rotational motion, including atmospheric drag, gravity gradient and solar pressure, were modelled as a system of differential equations and solved for using numerical integration. The most prominent of these is the gravity gradient between the two ends of the facility which manifests itself by affecting the rate of rotation and the rotation plane orientation. Another influence, caused by the oblateness of the earth, was the rotation of the right ascension of the ascending node which causes a precession of the orbital plane of the VGRF. Since the rate of precession was substantial (5.2° per day for USSR's Space Station Mir), the propellant requirement to perform in-orbit correction burns is prohibitive.¹ Orbital maneuvers to counteract the effects of atmospheric drag, however, were necessary to maintain Newton in orbit. Of the various orbit-raising strategies available, viable options included a single, large orbit-raising burn to maximum altitude and allowing the facility's orbit to decay to a minimum altitude, or many, small orbit-raising burns to keep the facility at the same altitude all the time. A strategy of raising the orbit and spinning up the facility with the same engine firings was discussed but abandoned due to the eccentricities that this method introduced to the facility's orbit.

Subsystem Design

Requirements of power, stability, and control for a rotating facility were met by using a truss as a primary support structure. Maximum bending and torsional strength, easy on orbit assembly, and reasonable total system mass were the design criteria of the truss. The entire truss system is composed of many identical truss bays, 5 m to a side, with 7.07 m diagonals, and each member having a 3 cm radius and 0.2 cm thickness, made of aluminum clad graphite epoxy.^{24,25}

Design constraints on Newton's power generation and distribution subsystem were: radiation environment, thermal environment, component degradation with time, and system interaction. The

low orbital altitude of Newton exposes it to non-ionizing radiation, unlike that found at higher altitudes. This determines the amount of radiation shielding required on the solar arrays. Another effect of orbiting at 51° at 500 km, Newton will be in the Earth's shadow from 0 to 35 minutes for each 94 minute orbit, which influences power storage performance requirements and mass. Thermal cycling of the arrays, up to 6000 cycles per year with a temperature variation of $\pm 80^\circ \text{C}$, determined the aging effects on power degradation. Each of the four, 400 m^2 solar arrays were composed of 62,500 $4 \text{ cm} \times 4 \text{ cm}$ GaAs/Ge solar cells with an efficiency of 22% and a derating factor of 0.75.²⁶ Overall performance indicators of the designed power system for Newton are the specific power, 10.1 W/kg, the area-specific power, 80.6 W/m^2 , and the specific cost, approximately 4.0 US \$/W.

The purpose of the main propulsion system was to initiate and control the spin-up and spin-down of Newton to induce the artificial gravity. To minimize propellant mass and for reasons of safety and structural integrity, the cluster of eight thrusters, four pointing in the direction of rotation and four pointing counter to it, were placed within a $5 \text{ m} \times 5 \text{ m}$ truss bay at the counterweight end of the VGRF. A total thrust level of approximately 10,000 N was required to attain the maximum g-level at the maximum spin rate in a reasonable burn time of 10 to 12 minutes. The R-40A engine,²⁷ commercially produced in the US, was chosen for the main propulsion system. Estimated amount of propellant (monomethyl hydrazine and nitrogen tetroxide) to spin/despun the facility to 1-g at 3 rpm was approximately 9.5 mt.

Newton has a large inertial momentum and angular velocity which leads to a large angular momentum. Attitude stabilization is due to the spin-stabilization effect of the angular momentum. Laser gyros were used to provide angular velocity stabilization using small correction thrusters as feedback actuators. Nutation oscillations due to impact, disturbance torques and thruster action

were damped by using induced magnetic eddy currents created by the conductive covering of Newton (aluminum) cutting through the Earth's magnetic field at 90°. Reaction control thrusters were located on both the manned module and the counterweight ends of the facility.

Requirements for the communications system were broken down into the categories of on board data handling, data transmission, and ground segment support. These requirements included provisions for up and down-link data encryption, and space/space communications for docking vehicles and neighboring stations (USSR's Mir). Nominal space/ground communications will use a high speed Ka-band link, docking and contingency communications will make use of an S-band frequency, and EVA will use a K-band communication link.²⁸

The environmental control and life support system (ECLSS) was required to provide a safe living environment for a crew of six with resupply every 180 days. The following ECLSS subsystems will require some level of resupply: temperature and humidity control, atmosphere control and supply, fecal waste management, fire detection and suppression, nutritional supply, biological/chemical contamination prevention and control, and propulsion integration. However, the air revitalization and water reclamation and management systems will be virtually closed using physiochemical processing methods.²⁹

Internal cooling of Newton is managed by the internal thermal control system (ITCS) and was designed to maintain all equipment within specified temperature tolerances at all times. Active cooling uses water in transport loops to collect heat and carry it to thermal bus exchangers. An estimate of 25 kW of waste heat transported by the ITCS included system, payload, and metabolic heat rejection. External radiators with a total design heat load of 70 kW (20 kW at 2° C and 50 kW at 21° C) were oversized by one panel at each temperature level.²⁹

OPERATIONS

Operations of the VGRF would begin with on orbit assembly of modules and subsystems such as the truss and solar arrays. After the VGRF was completely assembled, shown in Fig. 3,¹ resupply would occur every six months providing consumables, propellant and new experiments. Rendezvous operations would require facility despin and docking. Also included in operations are emergency procedures in the event of fire, loss of power, or use of the escape vehicles.

Assembly of the VGRF would require seven manned missions with some of the missions needing ELV's. Each assembly mission¹ would last a maximum of 14 days.

1. In the first mission, the US would launch a shuttle to deliver the first part of the module support structure, despun section, 70 m of main truss, truss bridge assembly structure, communication and power (solar arrays) systems, module RCS, and two robotic arms. The total mass would be 14,100 kg.
2. Energiya/Buran would be used by the USSR in the second mission to provide a man-tended facility. Payloads to be launched would be the command module and the first counterweight support structure totaling 30,250 kg. The Energiya tank would be added as the first counterweight.
3. The third mission would require two US launches. The habitation module, at a mass of 25,000 kg, would be lifted into orbit via Shuttle-C or equivalent (assumed to be available). The shuttle would be launched shortly thereafter carrying the remaining module support structure and would be used to conduct assembly operations.
4. On the fourth mission, the USSR would launch and assemble the laboratory module, air lock, and the second counterweight support structure. The total mass of these items is 35,250 kg and would require a Proton ELV to launch the air lock and

the Energiya/Buran to launch the laboratory module and second counterweight. The counterweight is the Energiya external tank.

5. The US would launch and assemble 130 m of main truss structure, counterweight propellant module and two escape vehicles on the fifth mission. The US would use the shuttle to deliver the total payload mass of 14,700 kg into orbit.
6. On the sixth mission, the USSR would launch and assemble the logistics module with consumables. This module is 15,000 kg and would be launched on the Energiya/Buran. Spin and systems testing would be conducted on this mission.
7. The seventh mission would be the first operational mission and would be performed by the US. Propellant necessary for this task would be launched on an ELV and the crew would dock with VGRF from the shuttle orbiter. Logistics resupply would also be provided as a shuttle payload during this mission.

The VGRF would be resupplied with propellants, ECLSS equipment,²⁹ replacement parts and new experiments every six months. A propellant mass of 7,500 kg would be necessary for attitude and altitude control. Necessary for each six month period would be about 4,450 kg of ECLSS supplies. A mass of 50 kg of spare parts has been allocated during each resupply mission. Experiment rack changeout would occur at an average rate of one per resupply mission since a typical rack has a mass of 800 kg.

Rendezvous with the VGRF from a manned or unmanned vehicle would require Newton to be despun. Crew members could be transferred via two docking ports located on the airlock and command modules shown in Fig. 4.¹ Manned vehicles include the USSR Buran, US Space Shuttle, the European Hermes and the Japanese Hope, assuming Hermes and Hope are operational at the time. Propellant resupply would occur at the third docking port, located in the counterweight

section, using unmanned vehicles. Propellant and consumables resupply would be provided by the unmanned USSR Progress or similar NASA and ESA ELV's.

Contingency operations would be necessary in the event of cabin fire, power failure and for emergency escape to a safe haven or escape vehicle. Fire hazard could be minimized by using fire retardant materials and keeping the oxygen concentration below 30%. Emergency lighting and alarm systems would be required in the event of a power failure with alarm classifications such as those from NASA document STD 3000.³⁰

CREW ISSUES

The Newton facility would be staffed with a maximum of six crew members at any one time: a Commander, a Deputy Commander, and four Mission Specialists. The Commander/Deputy Commander positions would revolve equally between the US and the USSR. The four remaining crew positions, as well as their allotment of time and space on board the facility would be allocated among the participating nations according to their contribution to the construction of the facility. The contribution breakdown would be as follows: 29% for the USSR, 29% for the US, 14% for ESA, 14% for Japan, and 14% for Canada. Each partner state would have the right to negotiate with other partners for additional time on board.

The crew members would have all the rights and privileges of astronauts according to Article V of the Outer Space Treaty¹¹ and the Rescue Agreement of 1968.¹² Each element of Newton would be governed by the jurisdiction of the state of registry, and each partner state would be responsible for the actions of its nationals. A Code of Conduct would be drafted and signed by each of the partner states. This code would be used on board to establish accepted rules of behavior for each of the Newton crew members. The Newton Commander would have the authority for personnel on board Newton as well as for any personnel of a vehicle docked to Newton during servicing.

English would be the official language on board the VGRF. However, each crew member would be required to speak at least one other language. Crew selection would be decided by each of the partner states, with the stipulation that crew candidates meet fundamental standards developed by a committee made up of the participating nations. Crew training would consist of individual, ensemble and on board segments.

COST AND FINANCING

Two main factors introduce a high level of uncertainty to both the cost estimate and the financial structure of Newton. The first is the complex international organization which adds to the complexity of political agreements, management of the program, and the technical interfaces. The suggested approach would be to minimize currency transfers, and instead insure that contributing countries receive the same value of contracts that they contribute to Newton. In the case of disagreement about the rate of exchange, the number of engineering man-hours or equipment weight could be employed as proxies for money by agreement of the partners.

The second factor is the very innovative character of the program, whose only valid references are the Space Station Freedom, and to some extent the Soviet Space Station Mir. While the cost of Mir is the subject of some discussion, Freedom's cost has grown steadily as plans on paper have developed into actual hardware. A rotating facility would require innovation in structural and control engineering when compared to Freedom and thus increases the difficulty of estimating development and on orbit pre-operational verification costs. Estimates which are presented here are comparable to those of Freedom; which seems reasonable as increased complexity may be offset by learning curve effects from using existing equipment.

The cost drivers considered include the level of technology and a relatively complicated international management with numerous interfaces. The cost estimates were based on the estimated

prices for similar subsystems and operations of Space Station Freedom, known launch service prices, and cost estimating relationships. The total cost is approximately 36 billion US\$, with a level of accuracy of 30%. A detailed breakdown of the total cost is given in Table 4. ¹ The financing of Newton is expected to be entirely government funded. Although there may be limited commercial applications the major benefits will be non-financial.

CONCLUSION

The political structure for the VGRF would be comprised of three levels of involvement based on the stated wants and needs of each country's space policy. Primary partners are the US and the USSR; the secondary partners include Canada, Japan, and ESA; countries such as China and India, as well as corporations, universities, or other agencies, could participate in the VGRF project after negotiations with the primary and secondary partners. A bilateral statement of intent between the primary partners, and a multinational intergovernmental agreement between all five of the primary and secondary partners would define the roles and responsibilities of each within the context of the entire project.

The primary goal of the VGRF would be to find a practical solution to the harmful effects of long term 0-g on the human body using artificial gravity, allowing a future manned mission to Mars. Long term human physiological deterioration from previous space flights reveal muscle atrophy, bone demineralization and cardiovascular deconditioning.^{5,6,7} These effects must be minimized for humans to successfully make the two to three year Mars mission. Secondary goals of Newton would be to conduct experiments in science processing and manufacturing to prepare for human planetary settlements which would require resource utilization.

Newton, shown in Fig. 3,¹ would be 200 m in length and is comprised of pressurized and unpressurized modules containing habitable environments and supply storage facilities. Attainable

g-levels fall between the range of 0.1 to 1-g at a spin rate not to exceed 3 rpm. The total dry mass and raw power requirements of the VGRF would be 235 mt and 187 kW, respectively. In order to make Newton reachable for all launch systems with little impact on their total payload to orbit capability, the orbital altitude and inclination were specified to be 550 km and 51°. Due to the greater orbital decay of Newton as compared to Mir, the two structures could not be co-orbiting even though they share the same orbit.^{1,9}

On orbit assembly and facility check out would require seven manned missions. Technology transfer issues were resolved by launching all US, Japanese, and some Canadian payloads by the US. The USSR would launch all Soviet, ESA, and the remaining Canadian payloads. Once the facility is operational, resupply would occur every six months requiring the facility to be despun. Facility design and crew procedures have been considered to handle emergency situations such as fire or loss of power. The VGRF would have two escape vehicles for emergency crew egress.

The Newton project was not only successful in producing a comprehensive report on a Variable Gravity Research Facility in LEO, but also in the intangible achievement of cooperation, collaboration and gained understanding among the international student and faculty participants.

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Table 1 Names of all individuals and their countries of citizenship who worked on the variable gravity research facility project.

ISU STUDENTS					
Bailey, Sheila	USA	Fry, Cindy	USA	Robinson, Ron	USA
Barnett, Brian	USA	Fukazawa, Hirofumi	JAP	Rose, Susan	USA
Beck, Thomas	FDG	Gu, Xuemai	PRC	Savastuk, Sergey	USR
Blokland, Renze	HOL	Guillaud, Vincent	FRA	Schmitt, Didier	FRA
Bobba, Fabiana	ITA	Huang, Weidong	PRC	Shimaoka, Eva	USA
Brice, Jim	USA	Jancauskas, Erin	AUS	Sitch, Jennifer	ENG
Casgrain, Catherine	CAN	Kashangaki, Tom	USA	Smith, Clive	ENG
Chanault, Michelle	USA	Komlev, Vladimir	USR	Spiero, François	FRA
Chiaramonte, Fran	USA	Le Merrer, Olivier	FRA	Takarada, Shinichi	JAP
Chincholle, Didier	FRA	Maxakov, Maxim	USR	Tsao, Ding-ren	TAI
Chowdhury, Dilip	ENG	McCuaig, Kathy	CAN	Tse, David	CAN
Colbeck, Pat	USA	Miller, Bill	USA	Uche, Nena	NIG
Cordes, Ed	USA	Miwa, Takashi	JAP	Verweij, Lucianne	HOL
Crepeau, John	USA	Monserrat-Filho, José	BRA	Vienot, Philippe	FRA
Dalby, Royce	CAN	Moore, Nathan	USA	Vix, Olivier	FRA
Davidian, Ken	USA	Munro, Shane	CAN	Wallman, John	USA
De Dalmau, Juan	SPA	Mordlund, Frederic	FRA	Williamsen, Joel	USA
Dunand, David	SWI	Pierce, Roger	USA	Wood, Lisa	USA
Eichold, Alice	USA	Poillier, Alain	CAN		
Elkin, Eugene	USR	Polunin, Andrey	USR		
ISU DEPARTMENT ASSISTANTS					
Belashov, Dmitry	USR	Perina, Maria	ITA	Valter, Kristina	CAN
Diedrich, Peter	CAN	Thangavela, Madhu	IND	Viirre, Erik	CAN
ISU FACULTY					
Atkov, Oleg	USR	Forman, Brenda	USA	Mendell, Wendell	USA
Boudreault, Richard	CAN	Legostaev, Victor	USR	Norton, David	USA
Crawley, Ed	USA	Lemke, Larry	USA	Tolyarenko, Nikolai	USR

Table 2 Each nation's work package.

Country	• Contribution
US/NASA	<ul style="list-style-type: none"> • infrastructure truss elements • module support structure • two reaction control systems • translating frame • launch services • habitation and propellant module
USSR	<ul style="list-style-type: none"> • two Energiya core vehicles • counterweight support structure • despun section truss • all antennae • airlock • command module • launch services
ESA	<ul style="list-style-type: none"> • laboratory module • crew escape vehicles • ground and on board communication and control facilities
Canada	<ul style="list-style-type: none"> • docking arm • two logistics modules
Japan	<ul style="list-style-type: none"> • power system (consisting of four solar arrays, radiators, and batteries) • data management system

Table 3 VGRF Mass Budget Breakdown.

Dry Mass	Metric Tons
Modules	<ul style="list-style-type: none"> habitation25.0 command30.0 laboratory30.0 logistics15.0 airlock (EVA)5.0 crew escape (2)11.4
Structures	<ul style="list-style-type: none"> primary truss2.0 module support1.0 counterweight (2)....100.0 counterwt. support (2) ..0.5 despun support.....1.5
Propulsion	tanks, engines, support. .4.0
Power	<ul style="list-style-type: none"> solar arrays (4)2.4 batteries (2)1.0 radiators (2)0.7
Mechanisms	<ul style="list-style-type: none"> despun section (2)3.2 translating frame1.1 robotic arm (2)1.0
Total Dry Mass234.8
Consumables	
Propellant7.5
Propellant Reserve2.5
Life Support4.5
Total Resupply Mass14.5

Table 4 Detailed breakdown of VGRF

cost in billions of US dollars.

COMPONENT	COST
Module section	12.50
Support	1.70
Despun section	1.90
Translating frame	1.00
Counterweight	3.30
Truss	0.05
Computer	4.00
Communication	1.10
Scientific equipment	1.00
Headquarters (10 years)	2.00
Crew training	0.12
Launch services	4.50
First year of operations	3.00
TOTAL	36.17

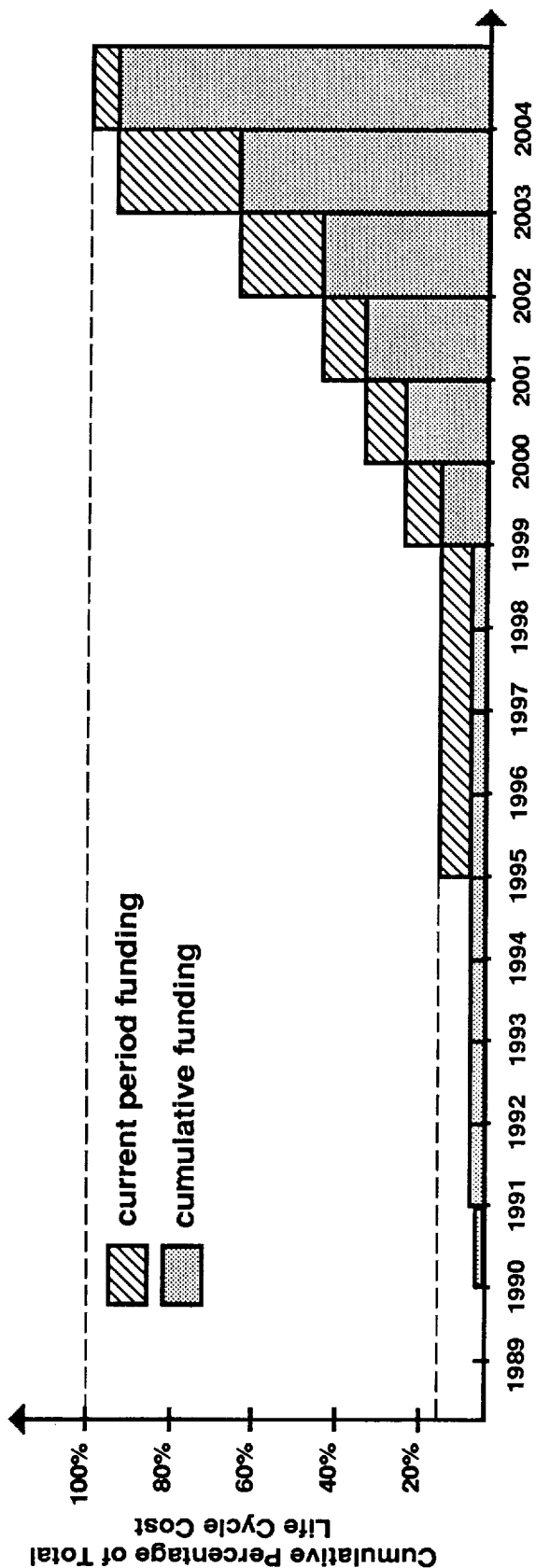
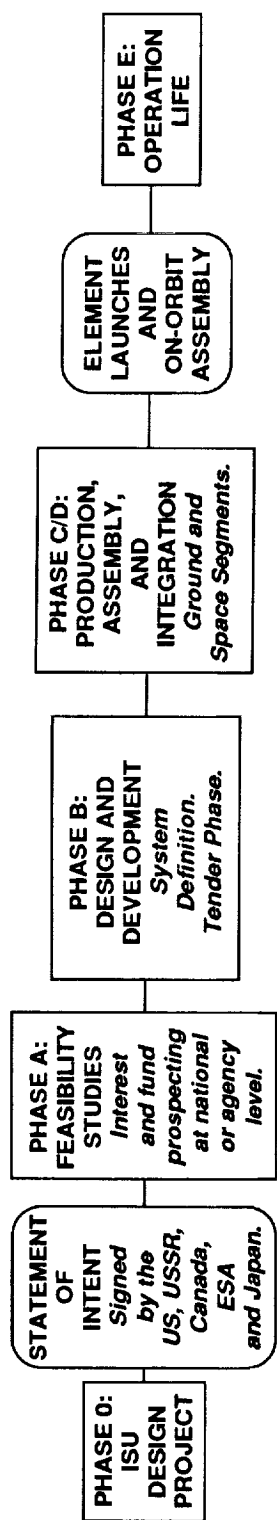


Fig. 1. Project Schedule

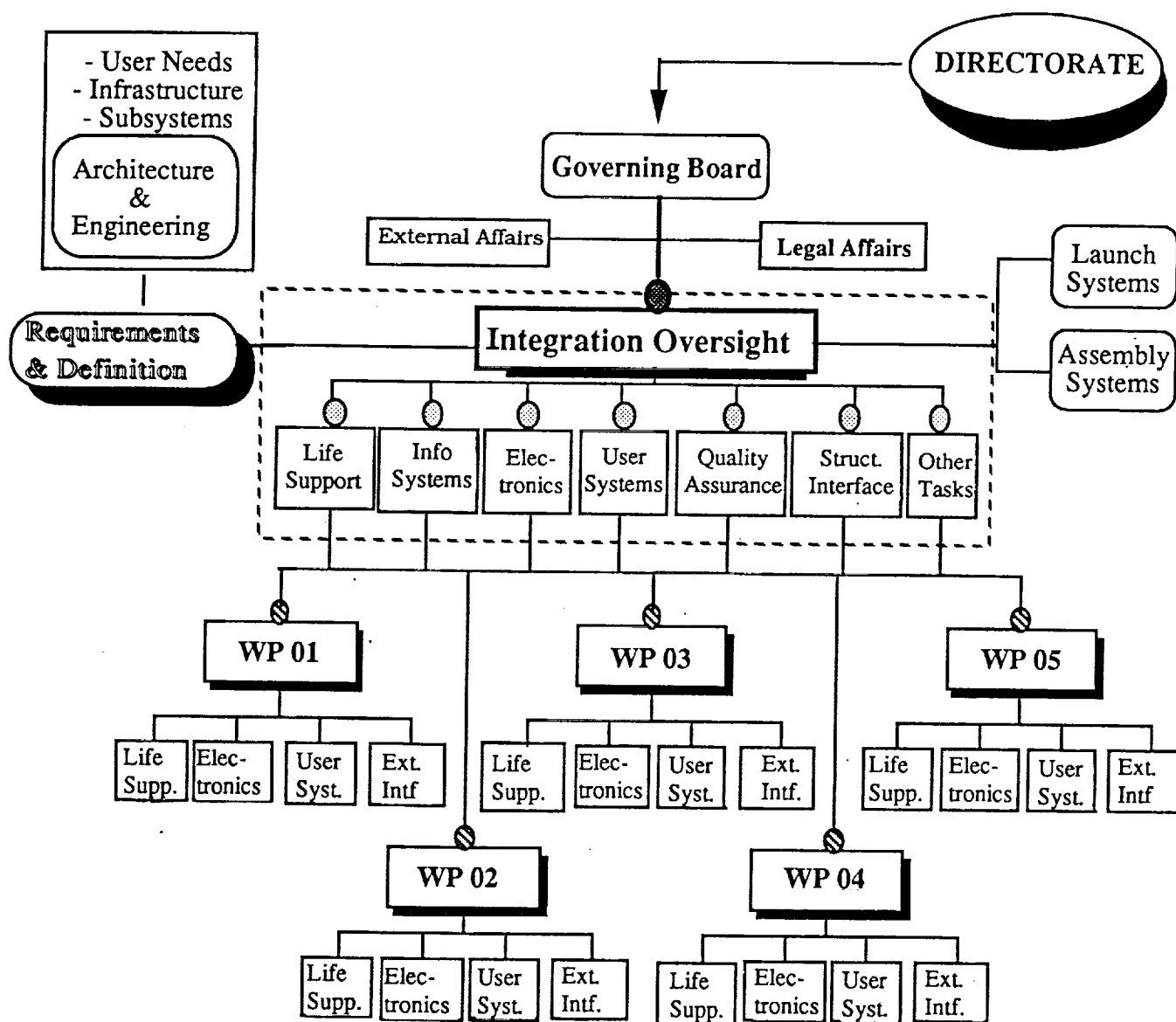


Fig. 2. Management Structure

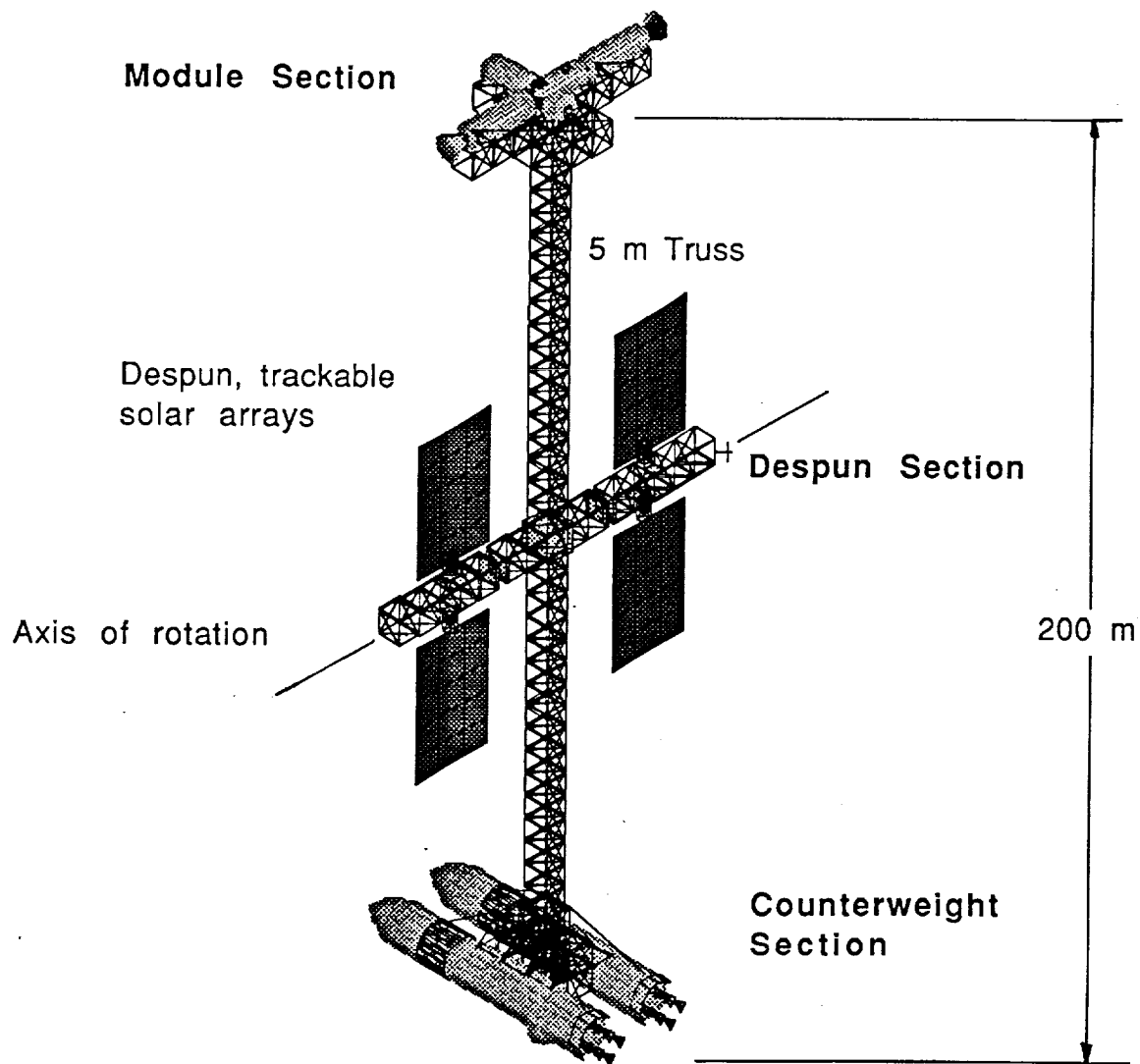


Fig. 3. Isometric View of Newton

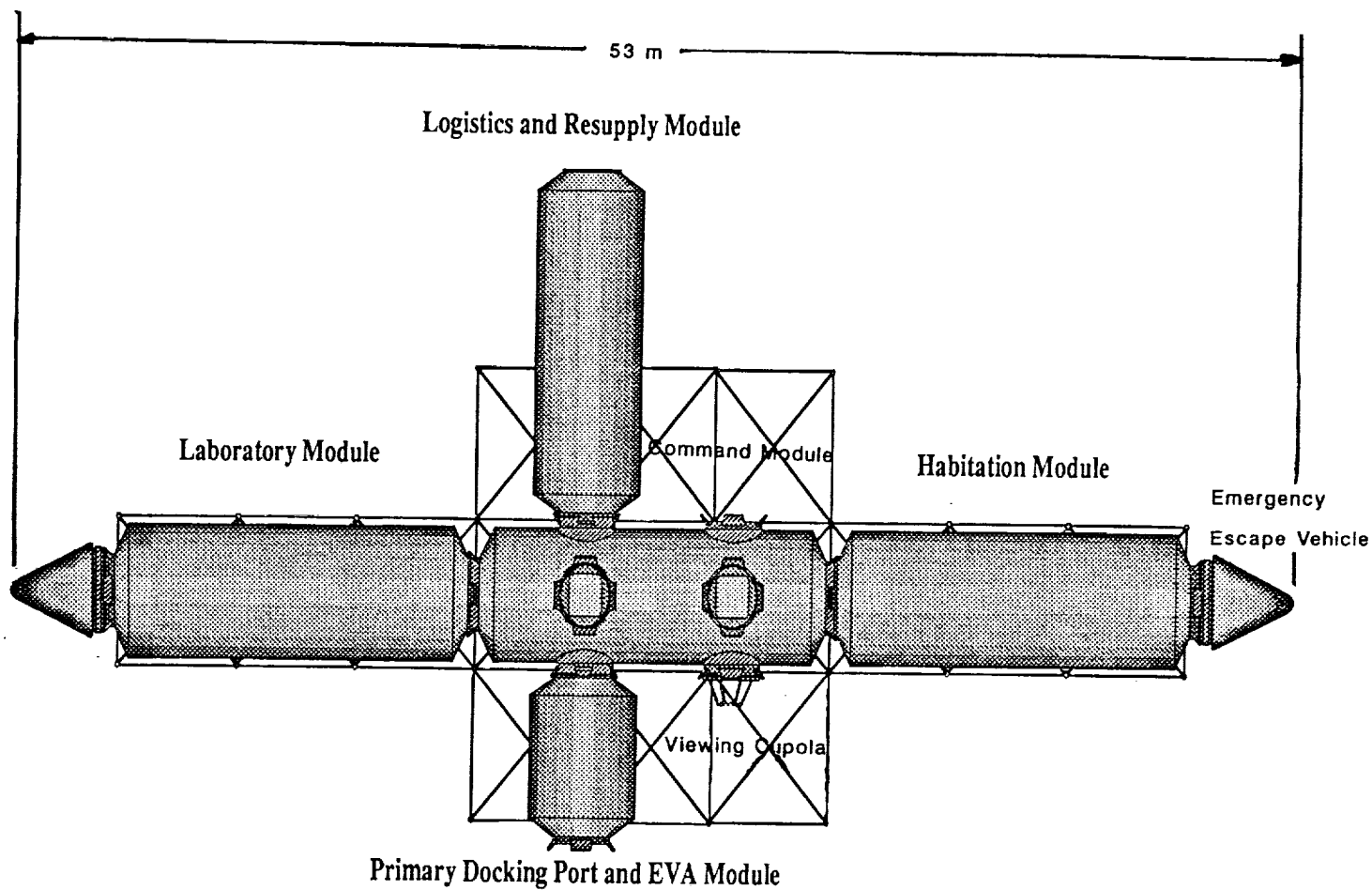


Fig. 4. Orientation of Newton's Manned Modules

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